AD-A147 031

(12)

DTNSRDC-84/047

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

BULK CAVITATION CAUSED BY A PLANE SHOCK WAVE

by

Benjamin M. Stow
John D. Gordon

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STRUCTURES DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

October 1984

DTNSRDC-84/047

BULK CAVITATION CAUSED BY A PLANE SHOCK WAVE

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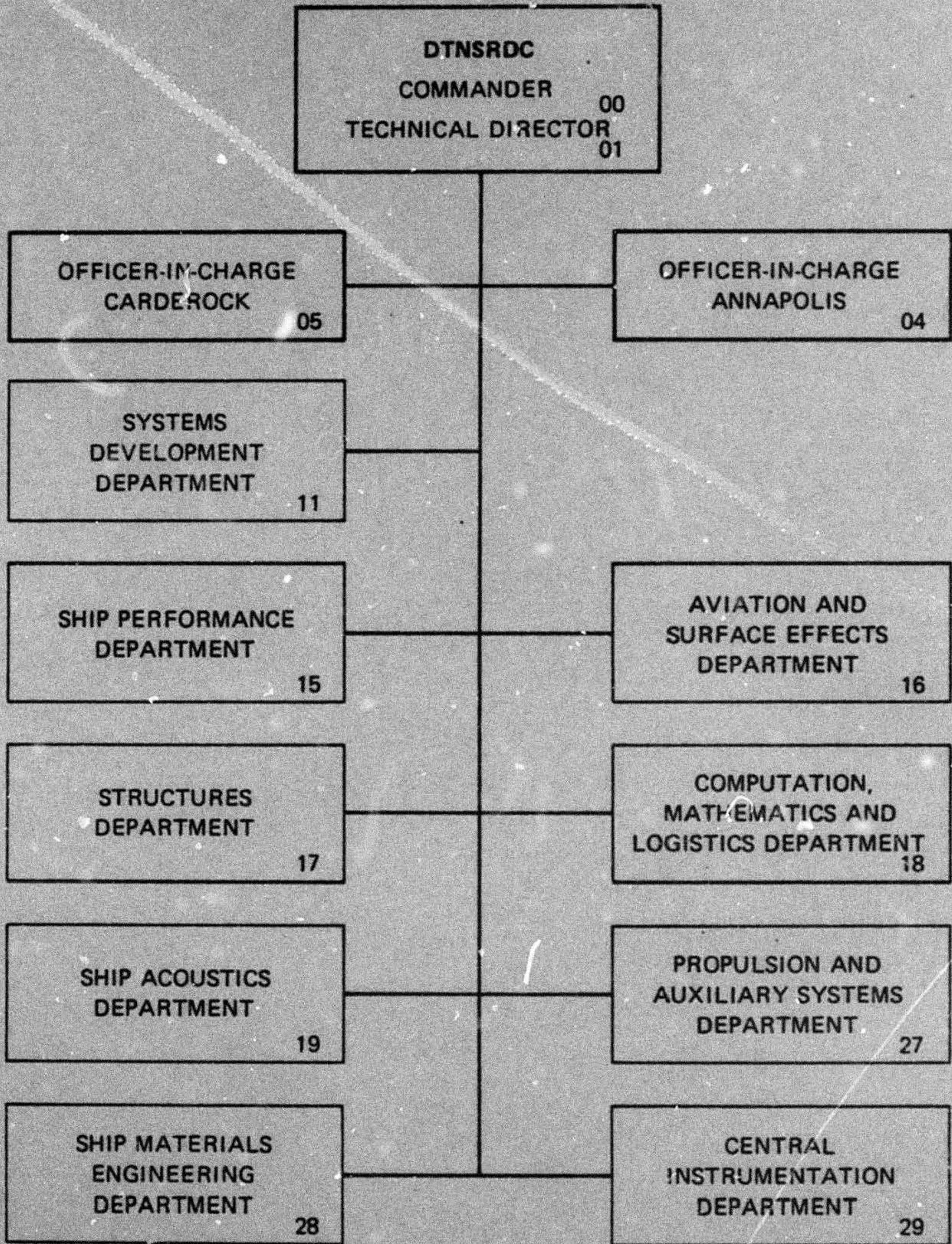

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DTNSRDC-84/047	2. GOVT ACCESSION NO. AD-A147031	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) BULK CAVITATION CAUSED BY A PLANE SHOCK WAVE		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Benjamin M. Stow John D. Gordon		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS David W. Taylor Naval Ship Research and Development Center Bethesda, Maryland 20084		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (See reverse side)
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE October 1984 13. NUMBER OF PAGES 19
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Surface Ship Loading
Cavitation Closure Depth
Cavitation Closure Time

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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DNA Subtask H02CAXSX338, Work Unit 02
Work Unit 1770-403

(Block 20 continued)

from the analysis. The results of the one-dimensional analysis can be compared with results from other analytical methods to determine the differences. Originator supplied keywords [illegible]

See [illegible] keywords

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TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

The bulk cavitation analysis method presented in this report eliminates the need to segment water for the purpose of solving simple equations of motion between water elements. The one-dimensional problem, analyzed in detail, demonstrates the ease of application of the method. Plots of cavitation closure, water pressure, and water particle velocity are provided from the analysis. The results of the one-dimensional analysis can be compared with results from other analytical methods to determine the differences.

ADMINISTRATIVE INFORMATION

The work reported herein was sponsored by the Defense Nuclear Agency under the Nuclear Weapons Effects Program, Subtask H02CAXSX338, Work Unit 02. Work was done by the David W. Taylor Naval Ship Research and Development Center, Underwater Explosions Research Division under Work Unit 1770-403.

INTRODUCTION

Because of the immediate analytical needs of the surface-ship shock-test program, the axisymmetric bulk-cavitation solution provided by Costanzo and Gordon[1*] emphasized quick results over an optimal mathematical description of the problem. The method used substitutes the labor of the computer (solving a multiplicity of collisions between segmented water elements) for the insight of the analyst (determining and integrating the appropriate equations that describe the accretion of the surface water layer). In keeping with the philosophy that the computer should be presented with the problem in the form best conditioned for solution, additional effort has been expended to seek an improved mathematical description that is based on the same physical assumptions.

OBJECTIVE

The primary objective of the analysis given in this report is to eliminate the need for segmenting water to solve simple equations of motion between water elements. This can be done by providing an equation governing the displacement of the surface water layer which is already integrated with respect to the water elements. This equation is to be general enough to apply to the axisymmetric bulk cavitation

*A complete listing of references is given on page 15.

problem. A secondary objective is to demonstrate an application of the new mathematical description by solving for the cavitation parameters resulting from a plane exponential shock wave moving along a line perpendicular to the water surface. A tertiary objective of the analysis is to investigate the effect of dropping a complicating term from the lower cavitation boundary displacement equation.

APPROACH

A momentum equation, similar to that employed by Waldo,[2] is used to describe the surface water layer velocity; however, this momentum equation is free of Waldo's assumption that water particle velocity kickoff occurs simultaneously along a vertical water column. This momentum equation is then integrated to yield the displacement of the surface water layer. The equation describing the displacement of a water particle in the cavitated state, along with the equation describing the displacement of a water particle at the lower boundary of cavitation, provide the remaining relationships necessary to support a solution for homogeneous water-layer accretion above-and-below the closure depth. The water hammer pressure is calculated from the collision velocities of the two water layers at closure.

SURFACE WATER LAYER DISPLACEMENT

A surface-reflected shock wave produces cavitation between two depths below the water surface by propelling free-water particles vertically between these depths. Starting at the upper cavitation boundary depth, the action of atmospheric pressure and gravity causes a thickening of the surface layer of uncavitated water, while, at the same time, the growing layer of uncavitated water is displaced with respect to the earth. To describe this motion mathematically, the water particles lying along a vertical column of undisturbed water are identified by a coordinate y equal to their depth below the water surface, and the motion of water particles is referred to inertial coordinates. Since the initial surface layer of uncavitated water starts accreting free water particles from underneath at the time of arrival of the relief wave at the upper cavitation boundary $y = a$, the time variable t in the equations is taken as zero at this point. Water particles underneath $y = a$ are kicked off with a vertical component of velocity U with respect to the earth at a time $t = T$. When gravity is accounted for as an upward 1-g acceleration of the earth, a water particle kicked off at time $t = T$ can be represented as having been kicked off with a velocity U + gT with respect to the stars. Treating the surface layer of uncavitated water as a rigid body having a velocity V with respect to the earth, the momentum per unit area of a water column of density ρ is $\rho y(V+gt)$, with respect to the stars. This momentum is equal to the sum of the kickoff momentums of the water particles reduced by atmospheric pressure P_a, as shown in Equation (1).

$$\rho y(V+gt) = \rho a U(a) + \rho \int_a^y (U+gT)\, dy - P_a t \tag{1}$$

In the model of the problem described by Equation (1), the initial layer of uncavitated water of thickness "a" is represented as being kicked off with a velocity equal to the water particle velocity at its under surface rather than the average velocity of the particles in the layer. This assumption is made to ensure that final cavitation closure lies between the upper and lower boundaries even when these boundaries coincide. When Equation (1) is divided by ρ and integrated with respect to time, Equation (2) describing the displacement D of the surface water layer is obtained as follows:

$$yD = aD_i(a) + taU(a) + t\int_a^y (U+gT)\, dy - \frac{1}{2}\frac{P_a}{\rho} t^2 - \frac{1}{2} ygt^2 + F \tag{2}$$

where D_i is the vertical component of the displacement of the water particle at depth y at the time of arrival of the relief wave at y, and $aD_i(a)$ is a constant of integration chosen such that at $t = 0$ and $y = a$, $D = D_i$. The letter F is the sum of the remaining parts of the integration of Equation (1).

$$F = \int_0^t [D\dot{y} - t(U+gT)\dot{y} + \frac{1}{2} gt^2 \dot{y}]\, dt \tag{3}$$

with the dot meaning differentiation with respect to time. Differentiating Equation (3) with respect to time and solving for D results in

$$D = F' + t(U+gT) - \frac{1}{2}gt^2 \qquad (4)$$

where the prime means differentiation with respect to y. Recognizing that D is also the displacement of a free-water particle at the time it joins the surface layer of uncavitated water, an additional equation for D is

$$D = D_i + (t-T)U - \frac{1}{2}g(t-T)^2 \qquad (5)$$

When D is eliminated from Equations (4) and (5), and F is solved for and integrated with respect to y, the result is

$$F = \int_a^y \left(D_i - UT - \frac{1}{2}gT^2\right) dy \qquad (6)$$

For a given depth y, Equations (2) and (5) solved simultaneously for t and D give the time it takes for the surface layer of uncavitated water to grow from a depth "a" to a depth y and the displacement of the surface layer at t.

CLOSURE FROM BELOW

Cavitation closure from below starts at the lower cavitation boundary y = b at relief wave arrival t = T(b), and proceeds upward until the surface layer of uncavitated water is met. The forces involved in closure from below are the elastic forces in the water below the lower cavitation boundary, the force of gravity acting on free-water particles above the lower cavitation boundary, and the force on the lower boundary due to the acceleration of the free particles as they are accreted. The elastic force in the water below y = b causes a water particle at y = b to be displaced upward, packing the water particles falling from above into homogeneous water. When a free-water particle is accreted by the lower homogeneous water, its velocity is increased from U - g(t-T) to V_b, the velocity of the water particle at

$y = b$, and the pressure P_p on the lower boundary due to the packing above is the time rate of change of momentum per unit area given by Equation (7).

$$P_p = [U-g(t-T)-V_b]\ \rho\dot{y} \tag{7}$$

The displacement D_b of the water at the lower boundary of cavitation is the same as the displacement of a free-water particle at the time it is accreted by the lower homogeneous water; therefore,

$$D_b = D_i + (t-T)U - \frac{1}{2}\,g(t-T)^2 \tag{8}$$

When $\dot{D}_b$ from Equation (8) is substituted for V_b in Equation (7), it is seen that the term in the parenthesis is the difference between the time derivative of D_b treating y as constant, and the time derivative of D_b treating y as a function of time.

A second equation for D_b can be determined from the pressure-time history at $y = b$, including the pressure on the lower boundary due to packing particles above, given in Equation (7). The two equations for D_b solved simultaneously give the depth-time relationship of the cavitation closure from below.

ONE-DIMENSIONAL SOLUTION

The general equations previously given will be illustrated by solving for the bulk cavitation parameters caused by a plane exponential shock wave moving perpendicular to the water surface. This case was chosen because the integrals of the exponentials appearing in the equations can be evaluated in closed form and attention can be concentrated on the method of solution rather than the labor of solution. The analysis is also valid for a plane exponential shock wave moving at an oblique angle β with the perpendicular, provided that the sonic velocity c in the normally incident solution be replaced in all equations with c_1, where $c_1 = c/\cos\beta$. The shock wave under consideration travels upward with a velocity c and a pressure-time history given by the equation

$$P = P_o e^{-\tau/\theta} \tag{9}$$

where P_o is the peak pressure above hydrostatic, θ is the shock wave time constant, and τ is the time after shock arrival at any depth y. At a given depth y, the time τ_c between shock wave arrival and the arrival of the relief wave from the surface is

$$\tau_c = \frac{2y}{c} \tag{10}$$

The depth of the upper cavitation boundary may be found by solving for the shallowest depth at which the surface reflected wave reduces the absolute pressure in the water to zero. This occurs when the absolute pressure just prior to arrival of the reflection is equal to the peak pressure of the reflected wave. Accordingly,

$$P_o e^{-2a/c\theta} + \rho g a + P_a = P_o \tag{11}$$

is the equation governing the upper boundary.

The lower cavitation boundary is the shallowest depth below the upper boundary at which the pressure discontinuity at relief-wave arrival can propagate downward without causing additional cavitation. This propagation becomes possible at the depth at which the absolute pressure in the water just prior to relief-wave arrival stops decreasing with depth and starts increasing with depth. Therefore,

$$\frac{d}{dy}\left(P_o e^{-2y/c\theta} + \rho g y + P_a\right) = 0 \tag{12}$$

$$\text{at } y = b, \text{ and } b = \frac{c\theta}{2} \ln \frac{2P_o}{\rho g c\theta}$$

At the lower cavitation boundary, the relief-wave pressure drop is equal to the absolute pressure in the water at y = b just prior to relief wave arrival less the packing pressure P_p, given by Equation (7). This relief-wave propagates downward linearly, and the water-particle velocity and displacement at the lower boundary of cavitation is the linear superposition of the incident and relief velocities and displacements. The equations for V_b and D_b will be written with time starting at relief-wave arrival at the upper cavitation boundary so as to be consistent with the general equations previously discussed.

$$V_b = \frac{P_o}{\rho c} e^{-\frac{t+[(a+b)/c]}{\theta}} + \frac{P_o e^{-2b/c\theta} + \rho g b + P_a}{\rho c}$$

$$- \rho \dot{y} \frac{U-g(t-T) - \frac{d}{dt}\left[D_i+(t-T)U-\frac{1}{2}g(t-T)^2\right]}{\rho c} \tag{13}$$

$$\text{for } t \geq \frac{b-a}{c}$$

$$D_b = D_i(b) + \int_{\frac{b-a}{c}}^{t} V_b \, dt \tag{14}$$

$$\text{for } t \geq \frac{b-a}{c}$$

For the one-dimensional case under consideration, the functions appearing in the equations are

$$D_i = \frac{P_o\theta}{\rho c}(1-e^{-2y/c\theta})$$

$$U = \frac{2P_o e^{-2y/c\theta} + \rho g y + P_a}{\rho c}$$

$$T = \frac{y-a}{c}$$

$$D_i(a) = \frac{P_o\theta}{\rho c}(1-e^{-2a/c\theta})$$

$$U(a) = \frac{2P_o e^{-2a/c\theta} + \rho g a + P_a}{\rho c}$$

$$D_i(b) = \frac{P_o \theta}{\rho c} (1-e^{-2b/c\theta})$$

The analysis will be illustrated by solving for the cavitation produced by a 700 psi, - 4 ms shock wave. For this shock wave,

$P_o = 700 \times 144\ \text{lb/ft}^2$
$\theta = 0.004\ \text{s}$
$P_a = 14.7 \times 144\ \text{lb/ft}^2$
$\rho = 1.9399\ \text{slug/ft}^3$
$g = 32.2\ \text{ft/s}^2$
$c = 5000\ \text{ft/s}$

and from Equations (11) and (12)

$a = 0.21359\ \text{ft}$
$b = 50.83706\ \text{ft}$

Results of the analysis are plotted with time starting with shock wave arrival at the water surface. This means that a/c has been added to the time variable t appearing in the equations before plotting.

Figure 1 is the cavitation closure as a function of time, and Figure 2 is the surface water layer displacement and lower boundary displacement as a function of time. The upper curves of these figures come from the simultaneous solution of Equations (2) and (5) and the lower curves come from the simultaenous solution of Equations (8) and (14). The time and depth at which the curves of Figure 1 come together are the origin of the water hammer due to cavitation closure. This water hammer is a square pulse of pressure equal to ρc times half the relative velocity at closure of the surface water layer and the lower boundary, and has a duration equal to the travel time to the surface and back. Plots of surface water layer velocity and lower boundary velocity are given in Figures 3 and 4, respectively. Figure 3 is from Equation (1) and Figure 4 is from Equation (13), with the addition of the velocity due to the shock wave from arrival to surface cutoff. The remaining figures shown in this report are piecewise constructions from linear shock wave

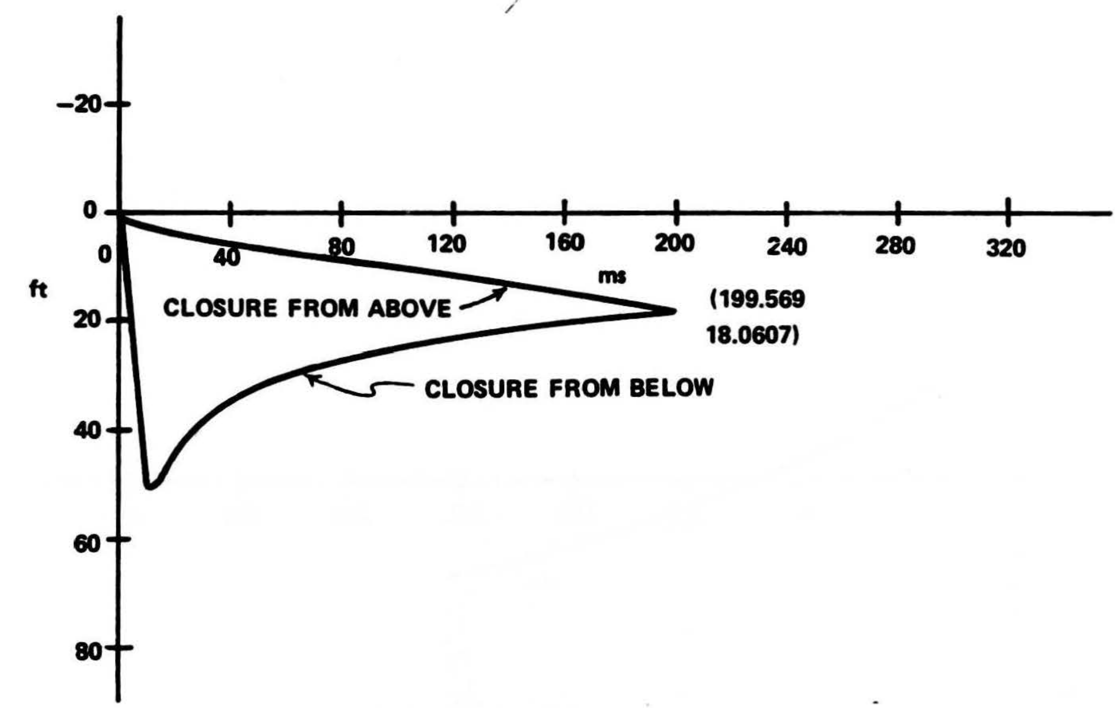

Figure 1 - Cavitation Closure

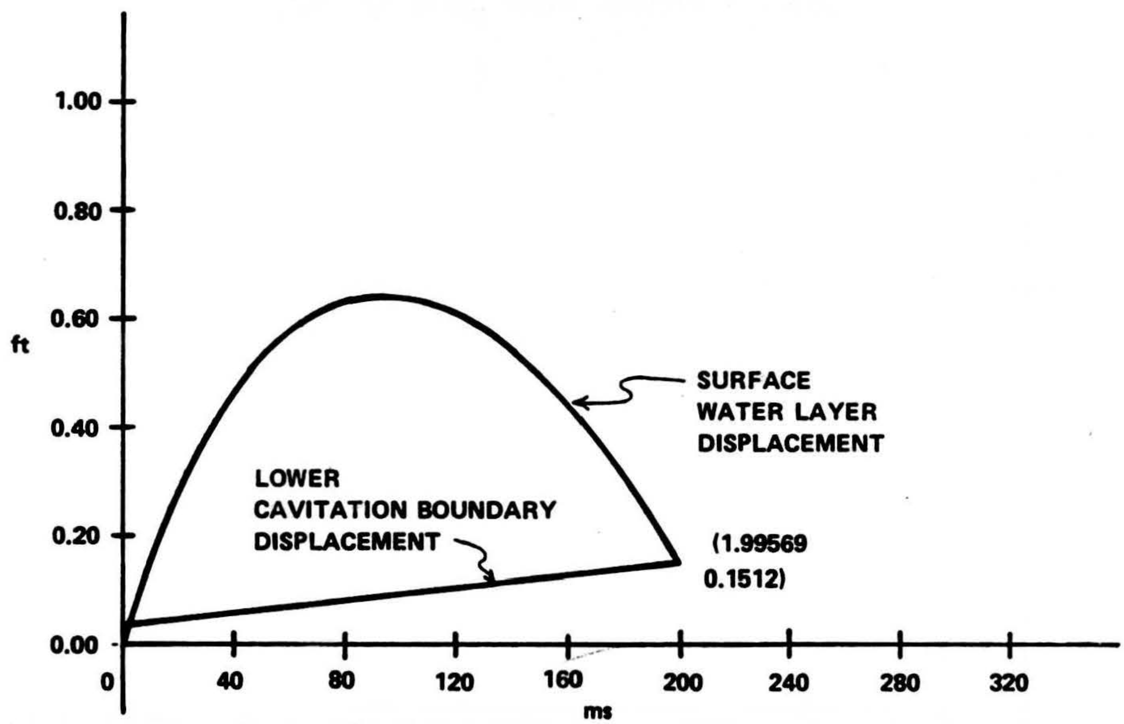

Figure 2 - Surface Water Layer Displacement and
Lower Cavitation Boundary Displacement

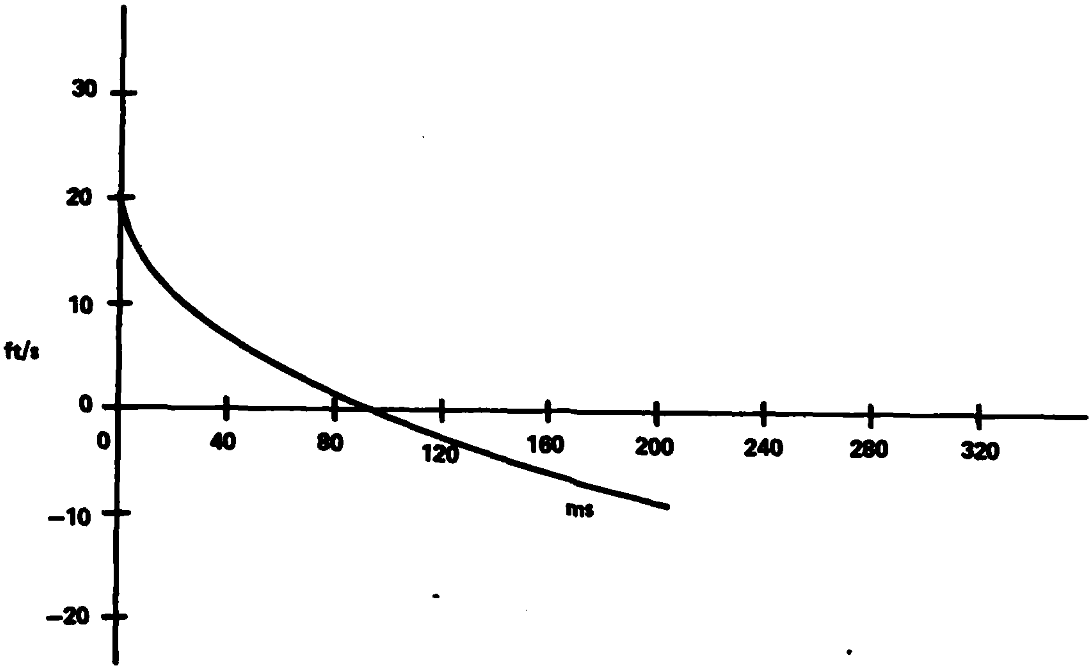

Figure 3 - Surface Water Layer Velocity

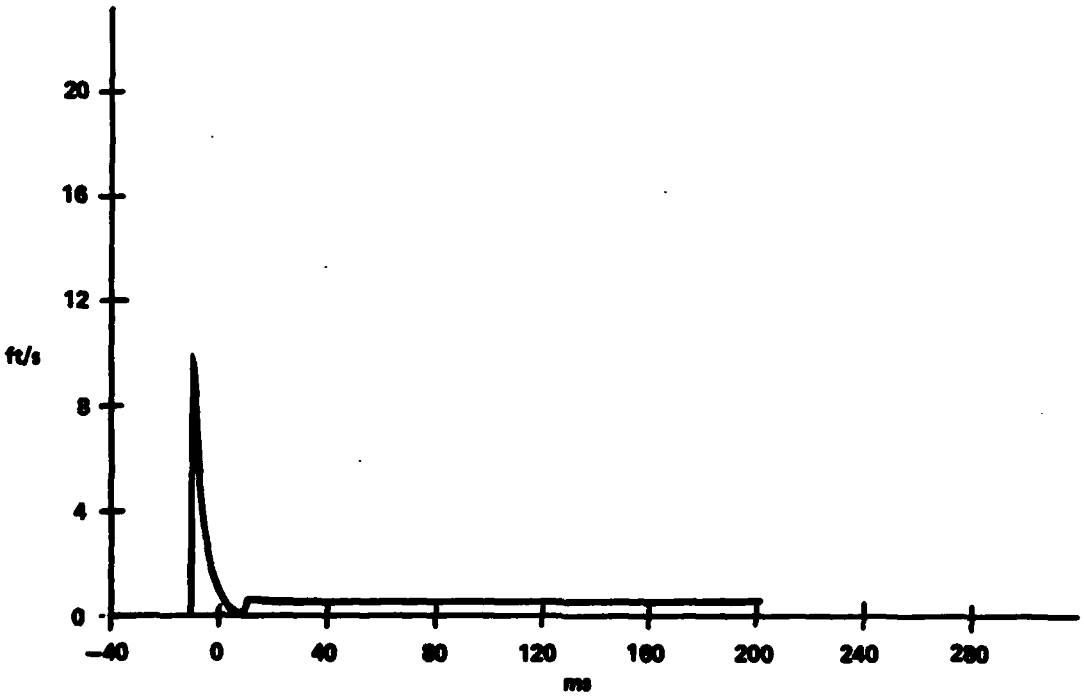

Figure 4 - Lower Cavitation Boundary Velocity

theory and the cavitation theory already outlined. Figure 5 is the pressure history at closure depth and shows the shock wave exponential reduced by surface reflection to absolute zero pressure until closure when the impact of the two columns of homogeneous water produces the closure pressure, which is also cut off by surface reflection. The corresponding water particle velocity at closure depth is shown in Figure 6. The straight-line portion of the plot between relief-wave arrival and cavitation closure is the particle in free fall. The pressure and water-particle velocity at mid-depth are shown in Figures 7 and 8, respectively. A salient feature of the water particle velocity in Figure 8 is the sudden drop in velocity when the particle is accreted by the surface water layer. Before accretion, the particle is in free fall. After accretion, the particle is moving with the surface water layer.

ANALYSIS NEGLECTING THE PACKING PRESSURE P_p

A second cavitation analysis for the same shock wave was made neglecting the packing pressure given in Equation (7). This eliminates the last term in Equation (13) for the lower boundary velocity. All other equations remain the same. A comparison of results from the two analyses with and without P_p is given in Table 1.

TABLE 1 - EFFECT OF P_p ON RESULTS

	Closure Depth (ft)	Closure Time (ms)	Pressure Pulse (psia)
With P_p	18.0607	199.57	306.84
Without P_p	18.0011	198.92	306.53

The comparison shown in Table 1 illustrates that including the force on the lower cavitation boundary due to the accretion of water particles from above is probably not worth the iteration effort required to solve Equations (8) and (14) simultaneously.

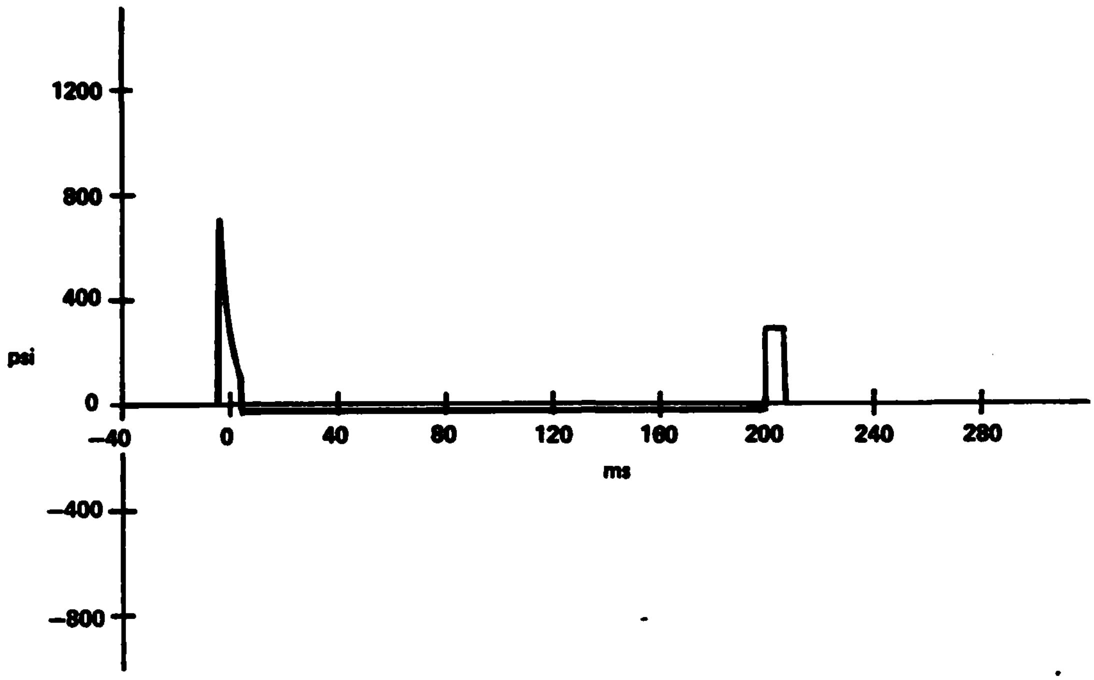

Figure 5 - Pressure at Closure Depth

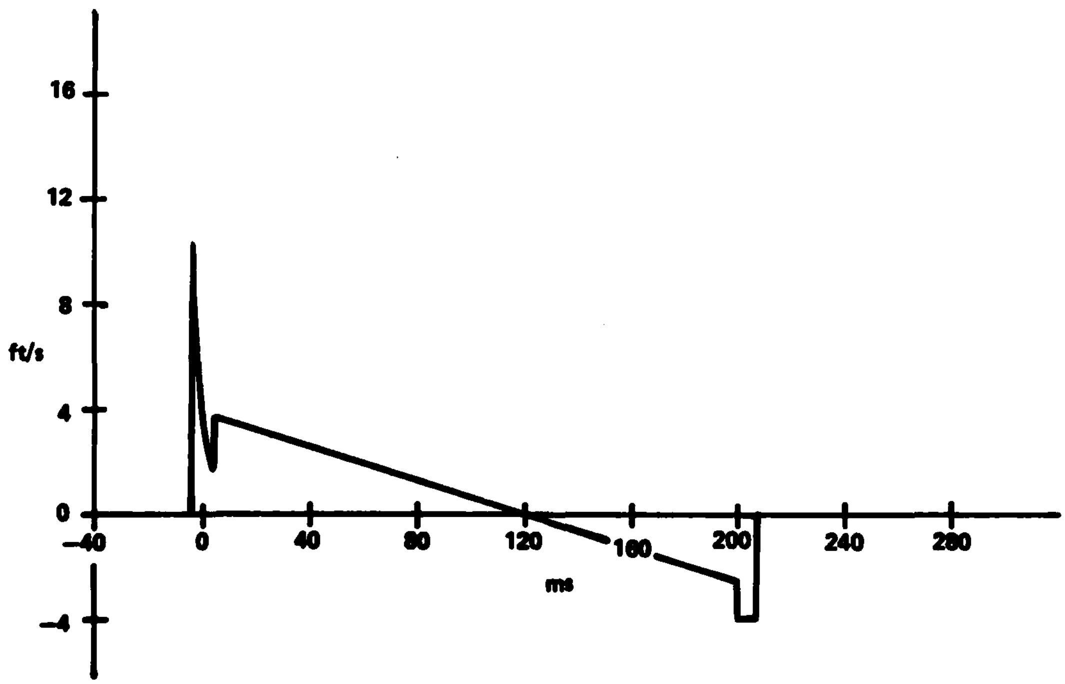

Figure 6 - Water Velocity at Closure Depth

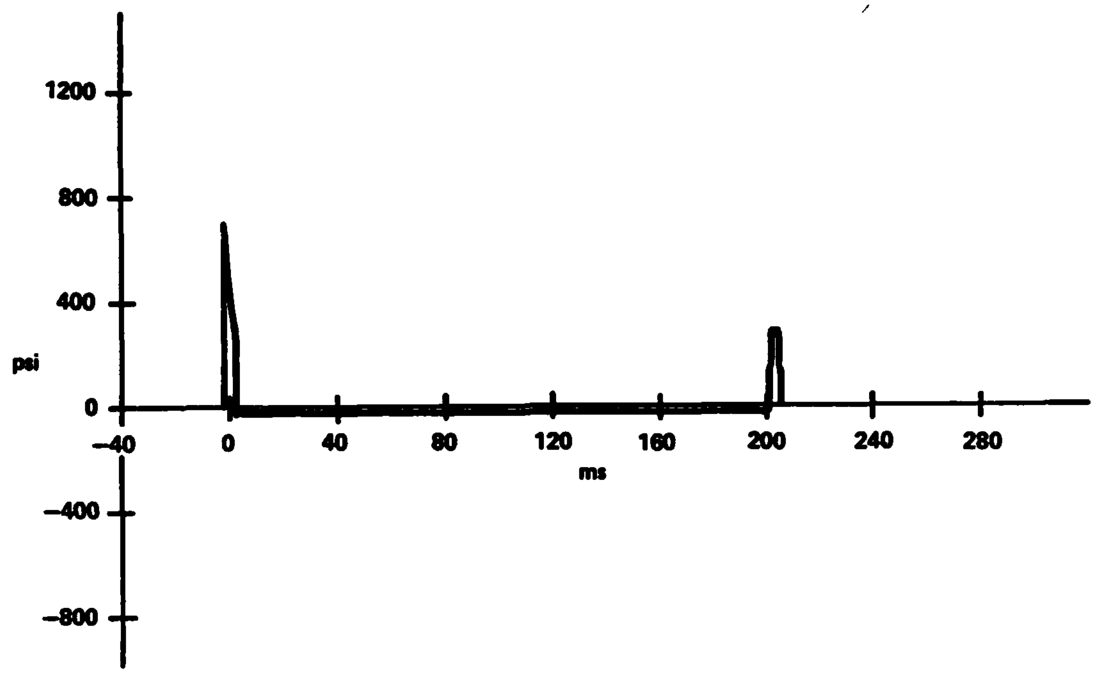

Figure 7 - Pressure at Midclosure Depth

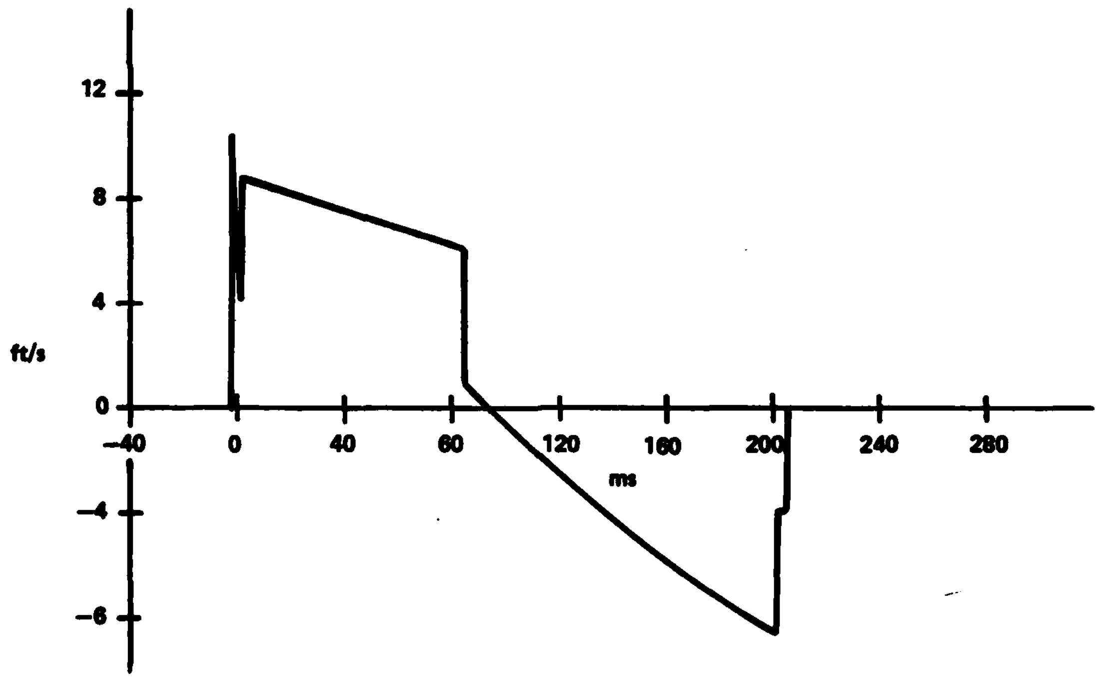

Figure 8 - Water Velocity at Midclosure Depth

CONCLUSIONS

The bulk cavitation analysis method presented in this report eliminates the need to segment water for the purpose of solving simple equations of motion between water elements. The one-dimensional problem analyzed in detail demonstrates the ease of application of the method particularly when a negligible term in the lower cavitation boundary displacement equation is dropped. The method should be used to rework the axisymmetric bulk cavitation problem in order to save computation time. The results of one-dimensional analysis should be compared with results from other analysis methods to determine the magnitude of any disagreement.

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1. Costanzo, F.A. and J.D. Gordon, "A Solution to the Axisymmetric Bulk Cavitation Problem," 53rd Shock and Vibration Bulletin (1982).

2. Waldo, G.V. Jr., "A Bulk Cavitation Theory with a Simple Exact Solution," NSRDC Report 3010 (Apr 1969).

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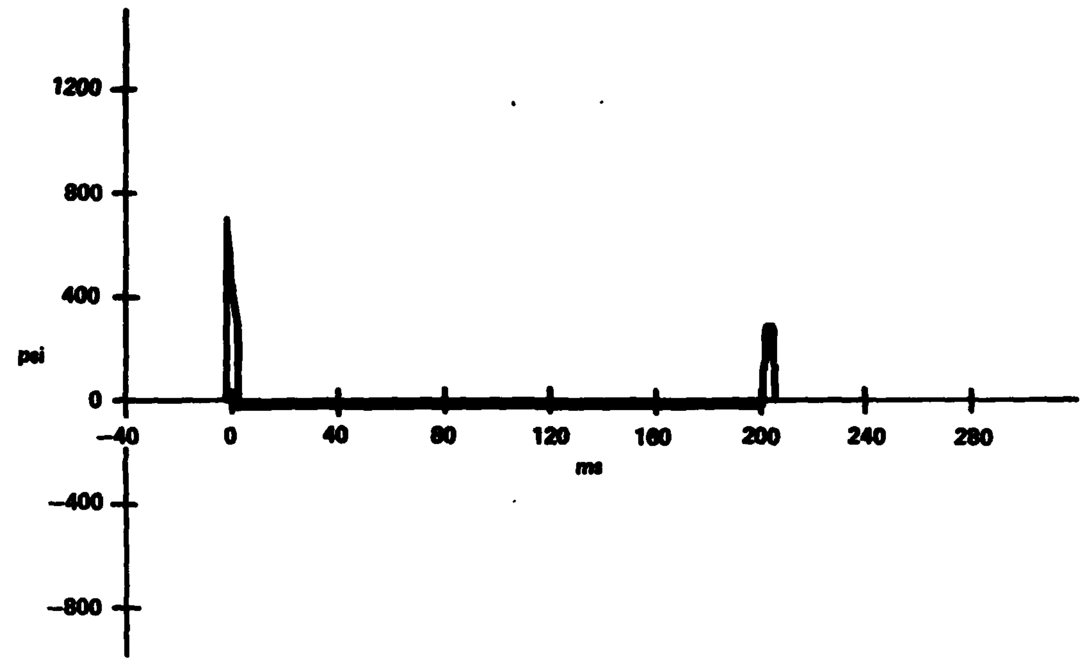

Figure 7 - Pressure at Midclosure Depth

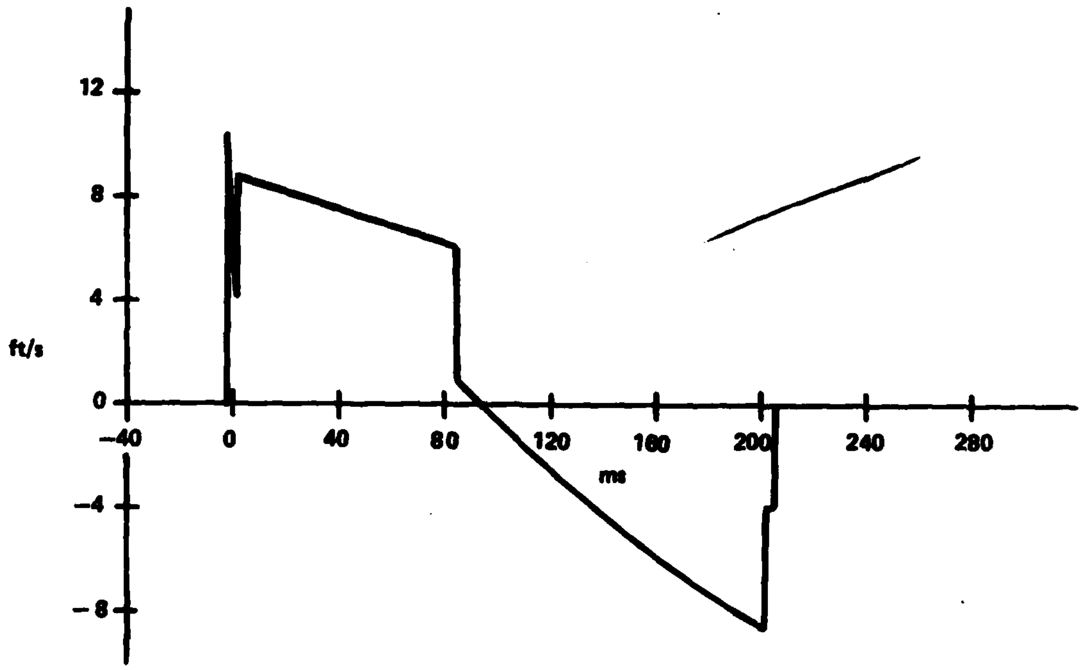

Figure 8 - Water Velocity at Midclosure Depth